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Analysis of Robust PID Control with Pre - Filter Using the Perfect ITAE Performance Criterion Applied to the Heavy - Duty Gas Turbine Fuel System

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***Abstract*— *The study of fuel control of the heavy-duty gas turbine arises naturally with the idea of providing a higher yield to the generation process, which is usually located in the first stage of generation, since the turbine is one of the main components in a thermoelectric plant along with the generator that is connected directly to the turbine. PID control is typically one of the most widely used control models in the industry because it provides the system with satisfactory performance according to the designer's choice using the ITAE performance criterion and a pre-filter can provide robust control for the system in question, which raises the reliability of the control even in the presence of variations of plant parameters. It is proposed to perform the sizing of this fuel control and with the use of MATLAB software to perform the simulation of the performance of the proposed control system, besides evaluating the control performance for hypothetical situations of parameter variations that can certainly occur in a system real subject to intemperes and interference from disturbances.*
***Keywords*— Thermoelectric Power Plant, Heavy-Duty Turbine, PID Control.**

I. INTRODUCTION

The increase in electric energy consumption is proportional to the population growth of a developing country, implying in several challenges that this demand for electric energy is met. In Brazil, currently works with the development of power generation projects aimed at diversifying the country's electrical matrix, in order to ensure the availability and reliability of the national electricity system.

In this context, the use of thermal power plants for electricity generation is on the rise, given the need to maintain reliable and more readily available electricity supply. Nowadays, combined cycle plants have become the main form of generation thermal power plants, since this model adds to the same generation power plant, the gas-fired power plants and the steam plant, resulting in an improvement in the thermal efficiency of the process in around 60%, compared to the isolated operation that has its yield of 30 to 40% [1].

The present work presents a fuel control proposal for a Heavy - Duty gas thermal turbine with the use of optimum performance indexes applied to the PID controller. This turbine is designed especially for industrial applications especially in power plants, where this is generally part of the first stage of combined cycle generation. The fuel control of the turbine directly implies the power generated by the generator coupled to the turbine axis, because if the fuel flow is too high, there will be an increase of the turbine rotation in moments when it is not necessary or flow at a time when on demand.

II. THEORETICAL REFERENCE

This stage of the work approaches the conceptual references of the elements necessary to apply the study and development of knowledge.

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2.1 COMBINED CYCLE THERMAL PLANTS

Combined cycle power plants are the most effective form of generation based on fossil fuel combustion such as diesel oil, natural gas, among others. Nowadays, combined cycle plants have become the main form of generation thermal power plants, since this model adds to the same generation power plant, the gas-fired power plants and the steam plant, resulting in an improvement in the thermal efficiency of the process in around 60%, compared to the isolated operation that has its yield of 30 to 40% [1].

2.2 HEAVY DUTY GAS TURBINE

Heavy - Duty Gas Turbines are turbine models designed especially for industrial applications, such models have a high robustness and wide range of power to the system. They have some important characteristics, such as low refrigeration, they can use gases with low calorific value, they usually have simple civil works, low vibration levels, easy operation besides allowing automatic control [2]. The gas turbine has the following components: compressor, combustion chamber and turbine. Its operation is characterized by the air compression that is carried out by the compressor, expansion in the turbine and addition of heat in the turbine realized by the combustion chamber. The heat injected comes from the burning of a fuel, whether liquid or gaseous.

When the turbine is in operation, the compressor compresses the atmospheric air and injects it into the combustion chamber where it is mixed with the fuel and is then burned, shown in Figure 1. The result of this combustion is the generation of hot gases that are expanded through of the turbine, converting thermal energy into mechanical energy on the shaft [3].

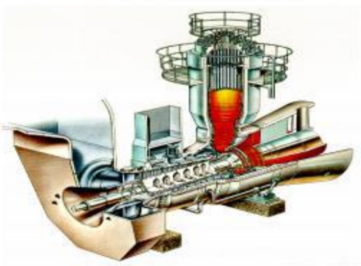

Fig. 1: Heavy Duty Gas Turbine Alstom GT8C, Source: [4].

In his work [5] presents the simplified mathematical model of the gas turbine with simple axis Heavy-Duty, serves as reference base for use in dynamic analysis of the system. This control representation is composed of three main stages of control which are the, acceleration, temperature and speed controls. In this model the main mesh is speed and the temperature and acceleration meshes act as limiters of material temperature and turbine acceleration, respectively [6].

2.2.1 Fuel Grid

The fuel grid consists of two valves in series, the first valve in question being responsible for controlling the pressure between them and is used to extend the ratio of the fuel flow from the maximum to the minimum during the start, the second controls the fuel flow in the turbine [7].

The response of the fuel system determines the responses of adjacent systems such as the pressure system which is changed as the response of the positioner of the first valve upon change. Figure 2 shows the fuel grid of the heavy-duty gas turbine with its variables and constants can on change depending on the type of fuel. And there will only be feedback due to pumping when using liquid fuel [8].

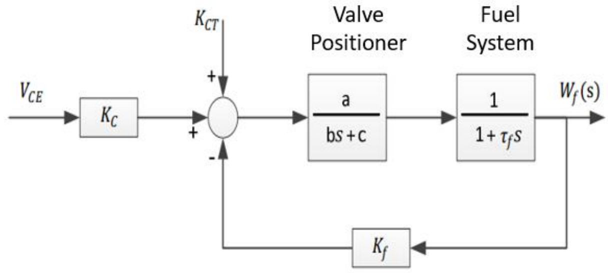

Fig. 2: Turbine Fuel System Plant, Source: [1]

At where:

VCE = Fuel demand signal (pu);

KCT = Constant that represents the own consumption of the turbine (pu);

KC = Constant that represents influence of the fuel demand in the turbine (pu);

Kf = Fuel system feedback (pu);

a, b, c = Values referring to the transfer function of the fuel inlet valve positioner (pu);

Tf = Time constant of the fuel system (s);

Wf (s) = Fuel flow (pu).

2.3 PID CONTROLLER

The PID controller is one of the most widely used compensation devices in the industry, this device consists of a three-term, proportional, integrative and derivative algorithm. The PID controller can be expressed in mathematical form in the time domain and domain of complex numbers in equations 1 and 2 respectively. Kp represents the proportional term of the controller, Ki represents the integrative term and Kd is the derivative term [9].

$$Gc(t) = \mathrm{Kp}E(t) + \mathrm{Ki}\int E(t)dt + \mathrm{Kd}\frac{dE(t)}{dt} \quad (1)$$

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$$Gc(s) = \mathrm{Kp} + \frac{\mathrm{Ki}}{s} + \mathrm{Kd}\, s \tag{2}$$

Figure 3 presents the generic model of the application of the PID control in a plant. The PID controller has been widely used in the industry for a long time, largely because this algorithm allows the designer to control the system in transient and steady-state responses with the same controller.

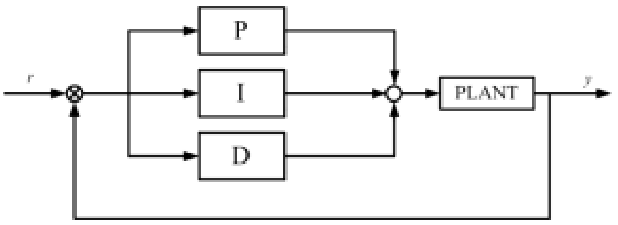

Fig. 3: Block Diagram of the PID Controller, Source: [10].

The PID controller introduces a transfer function with one pole at the source and two zeros that are set to design criteria. As is shown in equation 3.

$$\mathrm{Gc(s)} = \frac{\mathrm{Kd}(s^2 + as + b)}{s} \tag{3}$$

2.4 ITAE OPTIMUM PERFORMANCE INDEXES

In modern control systems system performance can be specified quantitatively, this specification is called performance index that can be used as a design criterion, in a system the minimization of the indexes can be directly related to reduction of fuel consumption for example. Conceptually performance index can be defined with a quantitative measure of a system's performance and is selected so that emphasis is given to the important specifications. A control system is considered optimal when the system parameters are adjusted until the index reaches an extreme, usually a minimum value [11].

The ITAE performance index is one of the criteria but used because it has better selectivity compared to other indexes that are addressed in [12]. The ITAE performance index is defined through equation 4.

$$ITAE = \int_0^T t\,|\mathrm{e(t)}|\,dt \tag{4}$$

In [13] the author demonstrates the expansion of the polynomial coefficients of a transfer function in its generic form. The transfer function can be verified in equation 5, this transfer function has a null error for a step input.

Tab. 1: Optimum polynomial coefficients of the ITAE index for a step entry

$$s + \omega_n$$
$$s^2 + 1{,}4\omega_n s + \omega_n^2$$
$$s^3 + 1{,}75\omega_n s^2 + 2{,}15\,\omega_n^2\, s + \omega_n^3$$
$$s^4 + 2{,}1\omega_n s^3 + 3{,}4\,\omega_n^2\, s^2 + 2{,}7\,\omega_n^3\, s + \omega_n^4$$
$$s^5 + 2{,}8\omega_n s^4 + 5{,}0\,\omega_n^2 s^3 + 5{,}5\,\omega_n^3 s^2 + 3{,}4\,\omega_n^4 s + \omega_n^5$$
$$s^6 + 3{,}25\omega_n s^5 + 6{,}60\,\omega_n^2 s^4 + 8{,}60\,\omega_n^3 s^3 + 7{,}45\,\omega_n^4 s^2 + 3{,}95\,\omega_n^5 s + \omega_n^6$$

Source: [13].

Table 1 shows the expansion of the ITAE coefficients for a step input of a polynomial characteristic of T (s) poles described in equation 5.

$$T(s) = \frac{Y(s)}{R(s)} = \frac{b_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0}. \tag{5}$$

III. APPLIED METHODOLOGY

This article is of a bibliographical nature, in the context of heavy - duty gas turbine fuel control, the bibliographic study is carried out using mathematical modeling articles using a block diagram, as well as articles, books and texts related to PID control design technique with optimal performance criteria.

The data referring to fuel system control variables are collected quantitatively in reference articles, however system performance comparisons are performed for different data in order to ascertain the robustness of the controller that is performed in a qualitative way. The PID controller design applied to the turbine fuel system is analyzed using the MATLAB computational tool, which enables the designer to observe the controller's performance over the controlled variable in the system in relation to transient and permanent regime errors.

IV. ANALYSIS AND DISCUSSION OF RESULTS

Based on the characteristics and data of the heavy - duty turbine fuel system studied where reference values for the variables of this system are developed either for use of the turbine with liquid fuel or gas. For the performance analysis of the fuel system represented by means of a block diagram in Figure 2, it characterizes the fuel system with its measured constants, which are presented in Table 2.

Tab. 2: Features of the Fuel System

Type	A	b	C	tf	Kf
Gas	1	0.05	1	0.40	0
Liquid	10	1	0	0.10	1

Source: [10]

In this work the entire study was carried out considering the use of liquid fuel because it is more used in this segment, so we can obtain the response of this

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reference system using MATLAB software. Figure 4 shows the turbine fuel system response to the values proposed in (WIRowen, 1983), where it is verified that this response has an Overshoot rate of 16%, peak time of 0.37 the time of establishment of 0.8 was established, and this performance occurs considering that the system does not suffer interference from the environment, that is, it is considered that the terms remain constant.

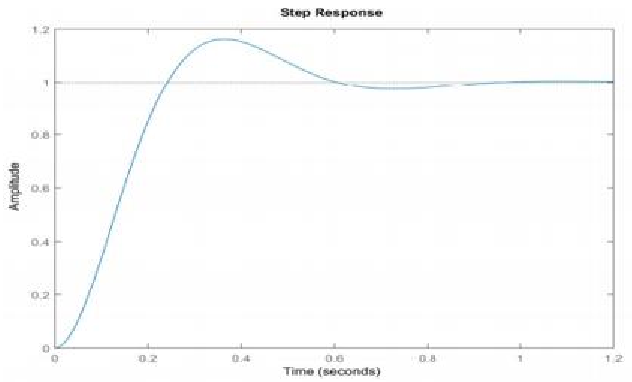

Fig. 4: Response to the reference fuel system step

However, for the application in the real environment where the variables are not linear, that is, it undergoes a change of parameters routinely, and it is necessary that the control systems provide robust performances of the projected response, in other words the system must maintain its satisfactory performance even with small changes in the variables due to external interference.

Based on this situation, it was proposed the implementation of the Robust ITAE PID controller with a pre-filter to perform the best of the system performance, besides providing a robust performance, making the system not sensitive to parameter variations as well as in the presence of external disturbances. Considering an ideal overshoot of 2%, peak time of 0.3 s, establishment time less than 0.8 s, besides adopting the coefficient of damping zeta equal to 0.8 and the natural frequency equal to 10 rad / s.

Tab. 3: Fuel System Characteristics for System Performance Testing

Test	Type	a	b	c	Tf	kf
1	Liquid	10	1	0	0.10	1
2	Liquid	9	0.5	0	0.10	1
3	Liquid	8	0.2	0.1	0.10	1

Source: [10]

Com base no desempenho desejado em relação à resposta ao degrau unitário do sistema de combustível foi realizado o dimensionamento do controlador PID utilizando o índice de desempenho ótimo ITAE, pré-filtro e executado a simulação do sistema com nova arquitetura que segue o modelo apresentado na Figura 5.

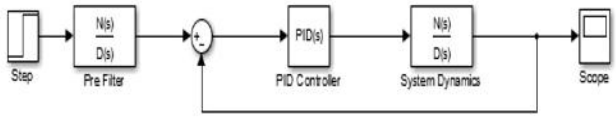

Fig. 5: Function Block Diagram of the PID controller application with Pre - Filter to the system

The first step was carried out with controller sizing and the pre-filter that met the ITAE performance requirements for test 1, using the characteristic parameters of the system made available in [5] with the objective of better performance of the response of the fuel system. Thus, using Table 2, which provides the optimal ITAE coefficients for a step input, in addition to the parameters already mentioned, the derivative, integrative and proportional coefficients of the controller are deduced, which are presented in Table 4.

Tab. 3: Controller gain table

Controller PID	Proportion	Derivative	Integrative
Gain	2.15	0.075	10

These coefficients were found starting from the analysis of the dynamic model of the system that is described in Figure 5 and the criterion of optimal performance ITAE.

$$Gc(s) = \frac{0.075s^2 + 2.15s + 10}{s} \quad (6)$$

Where in equation 6 has the representation of the mathematical model that describes the controller, with the analysis in the control mesh, the closed-loop transfer function of the system is presented by equation 7.

$$H1(s) = \frac{7.5(s^2 + 28.6s + 133.33)}{s^3 + 17.5s^2 + 215s + 1000} \quad (7)$$

Following, the choice of a pre-filter was made, so that it cancels the actuation of the controller's zeros in the final transfer function of the system, the pre-filter chosen is that described by equation 8.

$$Gp(s) = \frac{133.33}{S^2 + 28.6S + 133.33} \quad (8)$$

Finally, the final transfer function of this new system described as H (s) is presented by equation 9.

$$H(s) = \frac{1000}{S^3 + 17.5S^2 + 215S + 1000} \quad (9)$$

Finally, to obtain the system response, the MATLAB software was used to perform the simulation of the response to a step, which proved the expected performance expectation previously with an overshoot of 2%, rise time of 0.23 if the time of accommodation of

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0.75. Figure 6 shows the performance of the system for the application of the robust ITAE PID controller and the pre-filter.

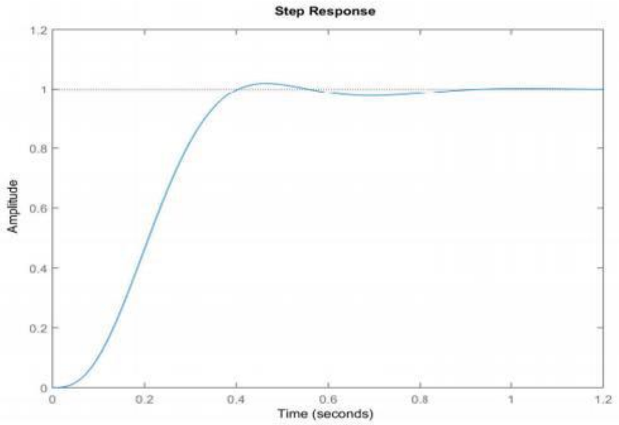

Fig. 6: Response from the system to test 1

With the robust ITAE PID controller already scaled in order to maintain the desired system response, then two tests were performed to verify the reliability of this control in test 2, the controller was applied to the system some parameters changed as shown in Table 3, these changes may be due to external disturbances or changes in the application environment. As soon as a new closed-loop transfer function is found just as a new pre-filter is to be used, in equations 10 and 11 the final transfer function and the pre-filter of the system respectively are presented.

$$\mathbf{H(s)} = \frac{\mathbf{1800}}{\mathbf{s^3 + 35s^2 + 387s + 1800}} \tag{10}$$

$$\mathbf{Gp(s)} = \frac{\mathbf{10}}{\mathbf{0.075s^2 + 2.15s + 10}} \tag{11}$$

After performing the simulation of the transfer function H (s), we obtained an overshoot rate of approximately 2%, time of rise 0.28 if time of accommodation of 0.60 s, that is, even with the system suffering variations of parameters the system is robust in relation to the response, Figure 7 shows the graph of the step response of the system.

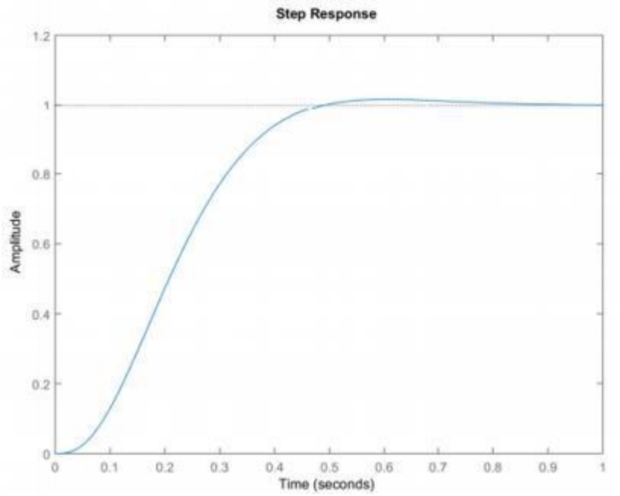

Fig. 7: Response from the system to test 2

Using the same reasoning, the simulation of the system transfer function was performed with the parameters described in test 3 of Table 3, where the transfer function is represented by equation 12.

$$\mathbf{H(s)} = \frac{\mathbf{4000}}{\mathbf{s^3 + 40.5s^2 + 865s + 4000}} \tag{12}$$

The pre-filter by equation 13, in addition to validating the robustness of the controller described by equation 6, the system response was very satisfactory with a small improvement, that is, the robust ITAE PID control is effective even with relatively large variations of the parameters of the system plan.

$$\mathbf{Gp(s)} = \frac{\mathbf{10}}{\mathbf{0.075s^3 + 2.15s + 10}} \tag{13}$$

The result after the simulation the system presented an overshoot rate of approximately 0% a rise time around 0.36s and establishment time of 0.7s.

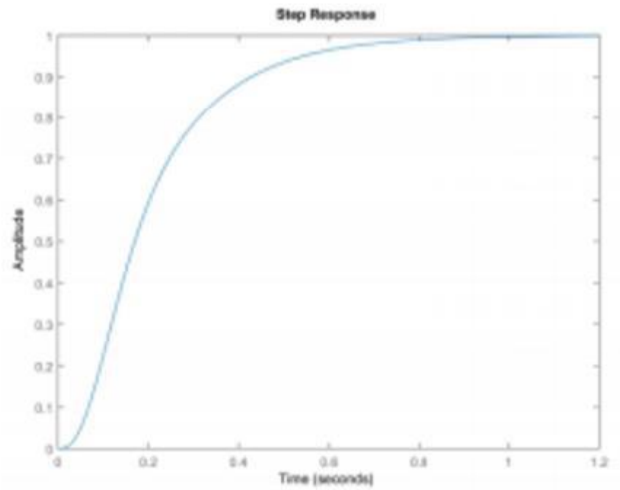

Fig. 8: Response from the system to test 3

Figure 8 shows the response to the unitary step of the fuel system with the variations of the parameters of test 3.

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V. CONCLUSION

With the continuous need for improvement in the electric power generation systems, in order to favor greater generation reliability, the engineering as a whole, and especially the electric, makes it possible to innovate and propose improvements to the generation systems.

A combined cycle thermoelectric consists of several systems. In particular, the turbine plays a key role in the process, so the heavy - duty turbine comes with a study source for individual performance improvement purposes that can affect the performance of other adjacent components, such as the generator.

Therefore, it is evident in this paper that the use of the robust ITAE PID control with a pre - filter to improve the fuel system performance of the heavy - duty gas turbine using liquid fuel, is efficient for applications in non - fully linear environments, or whether or not they change internal parameters due to interference from the external environment. This analysis and proposed solution to improve the system's response favors a reduction or consumption with greater fuel efficiency of the turbine, since it controls the system response to a demand demanded of output, even occurring possible variations of plant parameters, which implies a higher yield value in relation to the non - use of the robust ITAE PID controller applied to the heavy - duty turbine in the electric power generation system in combined cycle thermoelectric plants.

However, the application of the ITAE PID control theory is not restricted to the model developed here, quite the contrary, the application of this theory can provide the performance improvement of nonlinear systems in other areas of science, such as aerospace, electronics and communications, in addition to robotics itself.

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